

**Ductile-Ductile Beryllium Aluminum Metal Matrix Composite
Manufactured by Extrusion¹**

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Final Report

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13. ABSTRACT (Maximum 200 words) Recent advances in engineered materials have resulted in the development of several types of structural composites that are light weight, high strength and stiff. The beryllium-aluminum in-situ ductile-ductile composite alloy that is the subject of this proposal has the desirable properties of low density, high strength and high stiffness, as well as good thermal stability, high ductility and toughness not found in other composite materials. The goal of the Phase I effort was to determine the feasibility of producing a Be-Al composite wherein the composite is formed in-situ through solidification processing and worked by extrusion to form the final shape and impart mechanical properties. The major conclusions of the Phase I program were: (1) Production of Be-Al composites by casting and extrusion is a viable technology; (2) Cast Be-Al ingots can be extruded with either an aluminum or copper clad surface; (3) Excellent properties can be achieved in cast and extruded Be-Al rod; and (4) Be-Al composites can be cast and extruded into lengths of moderately complex shape, as demonstrated by the extrusion of the modified I-beam used in Phase I.				
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1.0 Introduction

Beryllium-aluminum alloys are unique, in-situ ductile-ductile metal matrix composite alloys. Cast and extruded beryllium-aluminum composite alloys are expected to have a unique combination of properties that are attractive for applications such as ground and space based interceptor and tracking systems that require minimum weight, high stiffness, good damping capacity and thermal stability. Compared with other metal matrix composites, cast and extruded beryllium-aluminum composites are expected to have the advantages of: (1) lower cost; (2) significantly higher ductility; (3) higher temperature capability; (4) less directionality of properties; (5) applicability of all conventional metal processing techniques; and (6) joining by conventional welding and brazing technology.

The current program is designed to develop a method for extruding a cast beryllium-aluminum composite, establish a basis for estimating the properties that can ultimately be achieved with an optimized process, and produce an extruded structural shape of moderate complexity. Specific technical objectives are as follows:

1. Develop an extrusion process suitable for beryllium-aluminum composites that maximizes product yield, minimizes processing steps, gives good surface finish, and is suited for producing complex shapes.
2. Determine mechanical and physical properties to demonstrate potential.
3. Define potential for property enhancements and cost reductions that could be achieved through continued development of this technology.

2.0 Background

Recent advances in engineered materials have resulted in the development of several types of composites that offer specific properties and characteristics not readily available from conventional monolithic materials. For structural applications, both organic matrix and metal matrix composites that are light weight, high strength, and stiff have been developed.

Typical of the organic matrix composites are the graphite fiber reinforced epoxy resin composites. Although these composites generally have high combined specific strength and specific modulus (e.g. $491 \times 10^6 \text{ lb}_f \text{ in/lb}_m$ specific modulus and $1.75 \times 10^6 \text{ lb}_f \text{ in/lb}_m$ specific strength for HMS graphite/3002M epoxy composite) they suffer from:

1. low thermal and electrical conductivity;
2. high moisture sensitivity;
3. limited elevated temperature capability;
4. poor thermal stability;
5. little if any ductility; and
6. highly directional properties.

In addition, organic matrix composites are expensive to manufacture and have limited forming and joining capability.

Metal matrix composites are attractive materials for applications such as ground and space based interceptor and tracking systems that require minimum weight, high stiffness, good

damping capacity and thermal stability. Advantages of metal matrix composites over organic matrix composites include excellent thermal conductivity, minimal moisture absorption, high temperature capability, greater ductility, and the possibility of being formed and worked by traditional metallurgical techniques. As a result, much effort has been expended to develop light metal matrix composites. Various types of metal matrix composites have been developed that combine a ductile matrix consisting of aluminum, magnesium or titanium, with either a continuous or discontinuous ceramic reinforcement phase such as graphite, silicon carbide, boron or alumina. A comparison of properties for some organic and metal matrix composites is provided in Table 1.

Table 1. Properties of Various MMC and OMC Materials

Material	Density (kg/m ³)	Tensile Strength (MPa)	Elongation (%)	Elastic Tensile Modulus (GPa)
Be-Al NMI 310 extruded/annealed	2131	413	15	227
graphite fiber/epoxy resin HMS/3002M				
0°	1578	689	0.4	193
90°		69	0.5	14
2014 Al/20%SiCp		489	2.5	106
SAE321 Al/Al ₂ O ₃ discontinuous fiber				
0°	2713	262	1.4	--
90°		248	0.8	--
6061 Al/B cont. fiber uniaxial				
0°	2630	1447	--	214
90°		172	--	138

Metal matrix composites are plagued by technical problems such as weak bonding between phases, limited long term thermal stability, and difficulty in achieving uniform mixing of constituents, as well as economic problems associated with high cost production methods and limited ability for net shape fabrication. However, these inherent limitations can be overcome to a large measure through the use of a ductile matrix combined with a ductile reinforcing phase. Ideally, if the ductile constituents are combined through in-situ processing, the resulting material will also be more uniform and more easily produced and fabricated into components.

Be-Al alloys are one type of ductile-ductile metal matrix composite. These materials are unique, in-situ composite alloys that are attractive candidates for many structural applications requiring lightweight materials that have high stiffness. Be-Al alloys have low density, high elastic modulus and substantial strength, combined with good ductility. They combine the light weight, high strength and stiffness of beryllium with the ductility and toughness of aluminum.

Be-Al alloys date from the 1960's. The Be-Al alloy known as Lockalloy (62Be-38Al) was developed by Lockheed and NMI and was produced by Kaweicki Berylco Inc. (KBI). Due to the state of casting technology for reactive metals and two phase alloys at that time, Lockalloy was produced by powder metallurgical (P/M) processes. However, recent alloy and process development work has resulted in the casting of high quality Be-Al alloys.

This development leads to the possibility of producing Be-Al composites through conventional metal casting and metal working technologies. Metal casting is a significantly more cost-effective method than P/M processing for Be-Al alloy production since it is a less process intensive manufacturing technique that affords a higher product yield. Preliminary data indicate that cast and extruded Be-Al alloys will have properties superior to those of P/M based alloys which, when combined with significant cost savings that can be realized compared with P/M produced Be-Al alloys will result in substantial economies.

Demonstration of the feasibility of producing Be-Al alloys via casting and extruding forms the basis for this phase I SBIR program. The specific alloy used is a 65Be-33Al-2Ag alloy that was developed during an extensive alloy development program at NMI for investment casting Be-Al alloys. The 65Be-33Al-2Ag alloy has been selected for this proposed program from a newly developed family of Be-Al alloys due to its good castability and expected suitability for extruded product.

3.0 Work Plan Summary

A two task effort was conducted to meet the objectives of this program. The tasks were broken down as follows:

- Task 1: Development of Extrusion Parameters
 - 1.1 Casting of Be-Al Billets
 - 1.2 Billet Coating Preparation
 - 1.3 Preliminary Extrusions
 - 1.4 Evaluation and Selection of Extrusion Parameters
- Task 2: Production of Structural Shapes
 - 2.1 Casting of Be-Al Billets
 - 2.2 Extrusion of Structural Shapes
 - 2.3 Mechanical Testing and Evaluation.

In Task 1, six extrusion billets were cast and extruded through a round die to develop extrusion parameters to use for the shaped extrusion of Task 2. The main variables that were examined focused on different methods of extrusion billet preparation. The specific variables were: (1) selection of can material; (2) method of application of can material; and (3) can thickness. Table 2 summarizes the billet preparation conditions used. The resulting extruded rods were evaluated for both surface and internal quality, and mechanical properties.

Table 2. Summary of Billet Preparation Methods Used for Task 1 Extrusions

Billet ID	Can Material	Can Thickness	Method of Can Application
590A	6061 Al	1.905 mm	external sleeve
590B	6061 Al	0.635 mm	external sleeve
591A	6061 Al	0.635 mm	plasma spray
591B	6061 Al	1.905 mm	plasma spray
589A	Cu	1.905 mm	external sleeve
589B	Cu	0.635 mm	electro-plated

For Task 2, three billets were cast and assembled using conditions selected based on the results of Task 1. These three billets were extruded through a die of moderately complex shape. The shape, a modified I-beam, was originally designed for the extrusion of an Al-SiC metal matrix composite. The first two billets were used to refine the extrusion conditions developed in Task 1. The final extrusion was made based on the parameters developed in the two tasks. The extruded shapes were evaluated for surface and internal quality, and mechanical properties.

4.0 Task 1: Development of Extrusion Parameters

4.1 Task 1: Billet Preparation

The casting process for the production of Be-Al ingots for this program involves vacuum induction melting the alloy constituents and pouring the melt into a cylindrical mold. The ingots were cast with a nominal composition of 65Be-33Al-2Ag (by weight percent). This composition was selected based on previous IRAD work, which demonstrated the suitability of this alloy composition for casting and extrusion.

For Task 1, three ingots were cast, each measuring approximately 47.5 mm diameter by approximately 200 mm length. The diameter of the ingots was increased slightly from the original plan to ensure that a high quality machined surface could be achieved on the ingots prior to extrusion billet preparation. Surface machining was required for surface preparation since the as-cast surfaces were rougher than desired. Each ingot was cut in half to provide six cylindrical billets for extrusion. Each uncanned/uncoated billet was machined to an appropriate diameter, depending on planned coating thickness, such that the diameter of the final coated billet in each case was approximately 40 mm.

Different pre-extrusion billet canning/coating techniques were evaluated to determine the optimal conditions that produce extrusions having the best surface quality. The can or coating helps prevent surface cracking and aids lubrication.

Three billet preparation techniques were evaluated. The first technique was to enclose the billet in a metal sleeve or can. The enclosed billets were then evacuated at elevated temperature and sealed by welding. Sleeves of 6061 aluminum were evaluated at thicknesses of 0.635 mm and 1.905 mm; a copper sleeve with a thickness of 1.905 mm was also evaluated.

The second billet preparation technique was to plasma spray a 6061 aluminum alloy coating onto two billets, with coating thicknesses of 0.635 mm and 1.905 mm. Plasma sprayed coatings were applied by Applied Coatings Inc., Columbus, Ohio. This plasma spray vendor required a knurled surface on the billets prior to plasma spraying, with the expectation of improved coating adhesion. However, several months elapsed between the time the billet surfaces were knurled and the time of application of the plasma sprayed coating, which may have led to a highly oxidized interface.

The surface of the final billet was plated with copper with a plated coating thickness of 0.635 mm. Difficulties encountered while developing a process for plating copper onto beryllium-aluminum by the original plating vendor required a change to a new plating vendor. The plating vendor used was Plating For Electronics Inc., Waltham, Massachusetts. Several Be-Al test coupons were used to select among several different plating techniques. The best results (i.e. a blister-free, smooth, uniform coating) were obtained by using a technique previously developed for coating pure beryllium.

A summary description of the specific billets prepared is as follows:

1. Billet 590A was prepared by enclosing the cast beryllium-aluminum ingot in a 6061 aluminum sleeve having a thickness of 1.905 mm.
2. Billet 590B was prepared by enclosing the cast beryllium-aluminum ingot in a 6061 aluminum sleeve having a thickness of 0.635 mm.
3. Billet 589A was prepared by enclosing the cast beryllium-aluminum ingot in a copper sleeve having a thickness of 1.905 mm.
4. Billet 591A was prepared by plasma spraying a coating of 6061 aluminum having a thickness of 0.635 mm onto the cast beryllium-aluminum ingot .
5. Billet 591B was prepared by plasma spraying a coating of 6061 aluminum having a thickness of 1.905 mm onto the cast beryllium-aluminum ingot .
6. Billet 589B was prepared by plating copper onto the beryllium-aluminum ingot to a thickness of 0.635 mm.

4.2 Task 1: Extrusion Processing

The six billets were extruded through a round die using similar extrusion parameters for each billet. Extrusion parameters were selected based on results from previous NMI IRAD work. The extruded rods were evaluated primarily for the effects of billet preparation on surface finish and on characteristics of the Be-Al/coating interface. Overall product integrity and tensile properties were also evaluated.

Graphite in oil lubrication (Lube-A-Tube) was applied to the extrusion press liner and extrusion die, and a graphite suspension lubricant (Spray Dag) was applied to the billets prior to heating. The two billets with aluminum cans (590A and 590B) and the two billets with aluminum plasma sprayed coatings (591A and 591B) were heated to 425°C, then extruded with a ram speed of 2.1 mm per second on the 340 ton capacity press at NMI. The two billets with copper cans (589A and 589B) were heated to 450°C, then extruded with a ram speed of 10.6 mm per second. The die size for all extrusions was 10.8 mm, corresponding to a reduction ratio (the ratio of the starting cross-sectional area to the final cross-sectional area) of 15.25:1. This reduction ratio was selected to be similar to the reduction ratio required for the Task 2 shaped extrusions.

4.3 Task 1: Results and Discussion

The three billets enclosed in Al or Cu sleeves, and the Cu plated billet, were successfully extruded. Examination of the surfaces of these extruded rods revealed small differences in surface quality. The best surface quality was seen for the rod extruded from billet 589B, which had been plated with a thin layer of copper. The surface of this rod was smooth and uniform over the entire length of the rod. The rod extruded from billet 589A, which had been canned in a thicker copper sleeve, also had a uniform surface that was only slightly rougher than the surface on 589B.

The surface of the rod extruded from billet 590A, which had been canned in a thicker aluminum sleeve, was rough over the entire length of the rod. The appearance of this rod suggested that the billet had either been overheated, or that insufficient lubrication had been used. The surface of the rod extruded from billet 590B, which had been canned in a thin aluminum sleeve, was smooth except for a few blisters. Although the overall surface quality of the billets extruded with copper cladding was better than the extrusions made with aluminum cladding, the results suggest that further development should lead to the capability of producing high quality beryllium-aluminum extrusions with aluminum cladding as well.

Microstructural evaluation of transverse and longitudinal sections from each extruded rod was done with the scanning electron microscope (SEM). Samples were evaluated for cladding uniformity, cladding/beryllium-aluminum interfacial features, and general microstructural features of the extruded composite. Micrographs of longitudinal and transverse sections of each extruded rod are shown in Figures 1 and 2.

The extruded beryllium-aluminum microstructures show uniform deformation of the beryllium phase (dark imaging phase) and of the aluminum phase (light imaging phase). Uniform cladding thickness is observed on all longitudinal sections (figure 1 b and d, figure 2 b and d). Cladding thickness on extrusions 589A and 590A measures 580µm; cladding thickness on 589B and 590B measures 250µm and 270µm respectively.

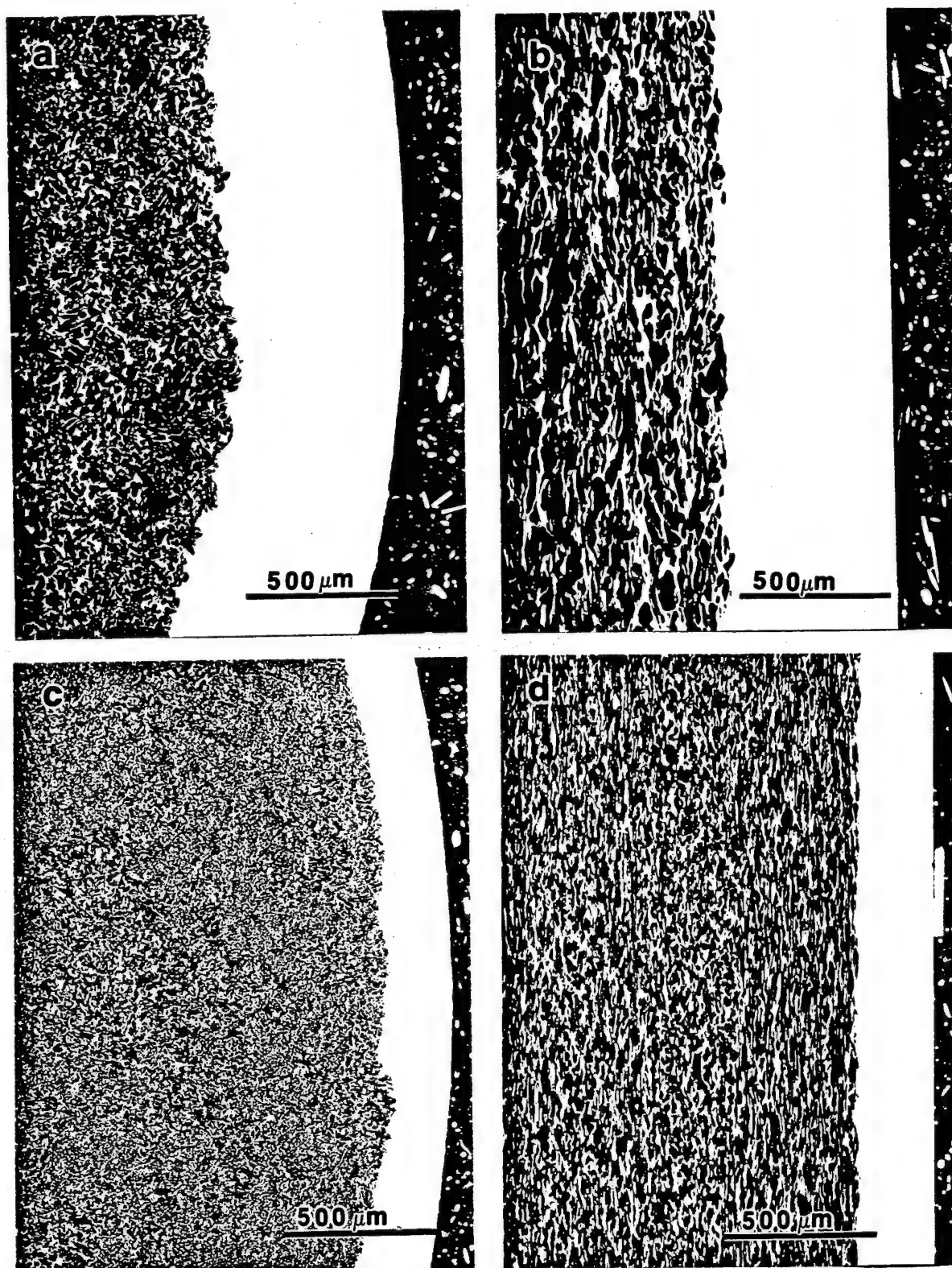


Figure 1. Backscatter electron images showing Cu clad surfaces of extruded Be-Al. (a) 589A (billet with thick Cu sleeve), transverse section, (b) 589A, longitudinal section, (c) 589B (billet with thin Cu plating), transverse section, (d) 589B, longitudinal section.

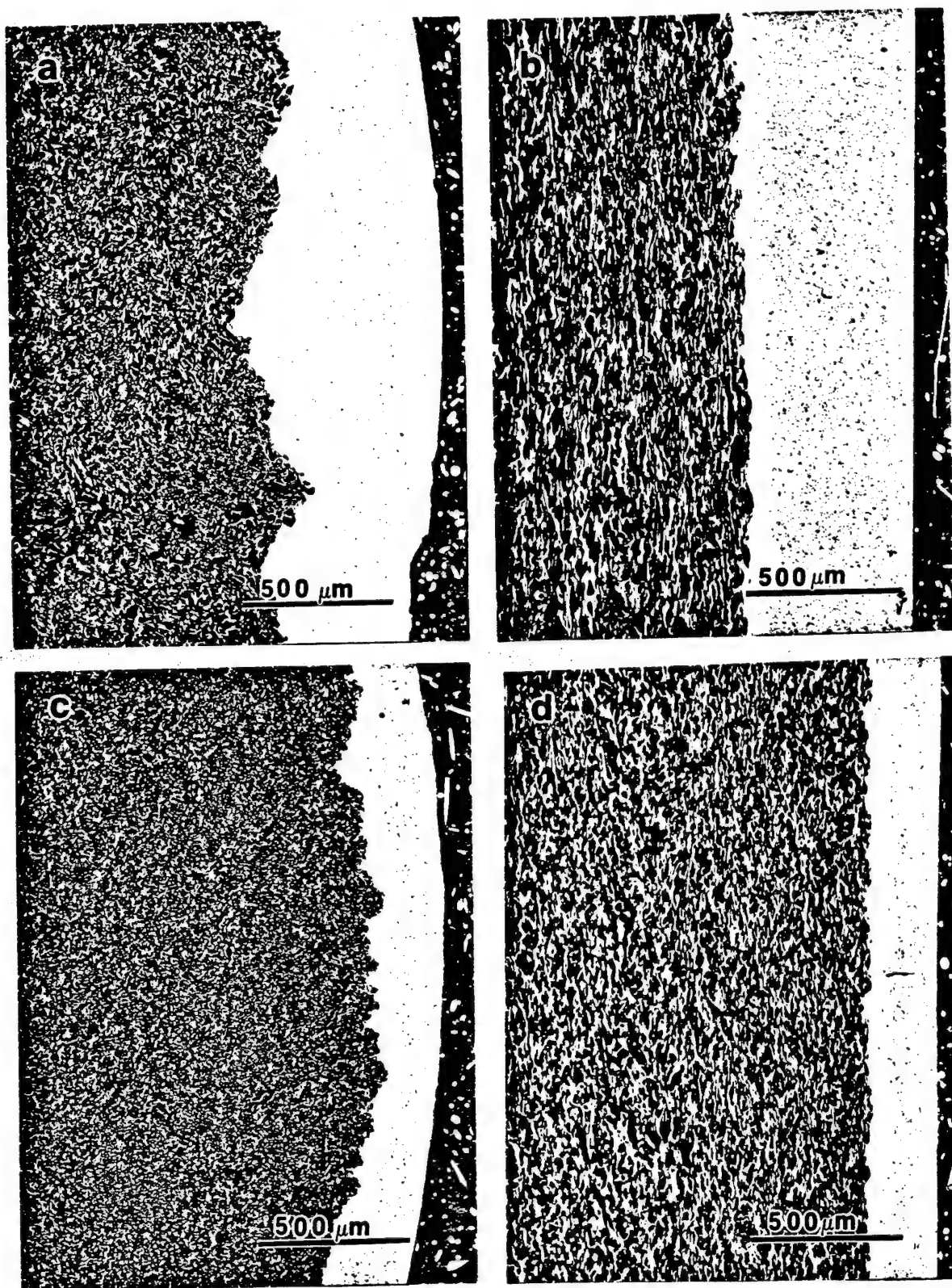


Figure 2. Backscatter electron images showing Al clad surfaces of extruded Be-Al. (a) 590A (billet with thick Al sleeve), transverse section, (b) 590A, longitudinal section, (c) 590B (billet with thin Al sleeve), transverse section, (d) 590B, longitudinal section.

Transverse sections (Figure 1 a and c, figure 2 a and c) show greater roughness at the cladding/beryllium-aluminum interface, particularly for the aluminum clad extrusions. Further improvements to interfacial roughness may be achieved by providing a better surface finish on the beryllium-aluminum ingots prior to canning.

Higher magnification examination of the aluminum cladding/beryllium-aluminum interfaces for extrusions 590A and B revealed continuity between the aluminum cladding and the aluminum phase of the beryllium-aluminum composite. Examination of the copper cladding/beryllium-aluminum interfaces for extrusions 589A and B showed the presence of a thin copper-aluminum intermetallic layer ($<4\mu\text{m}$) at the interface.

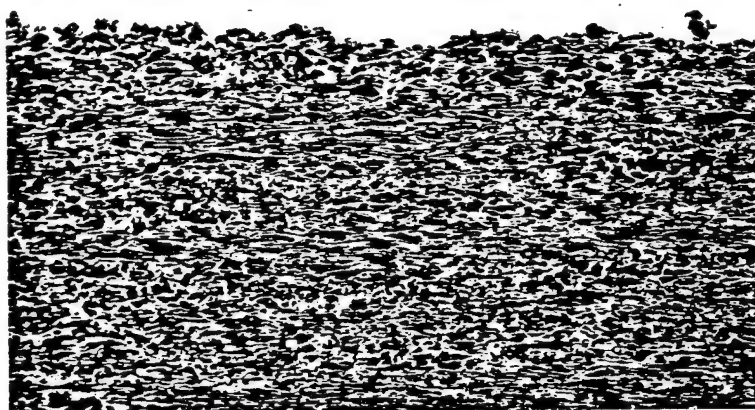
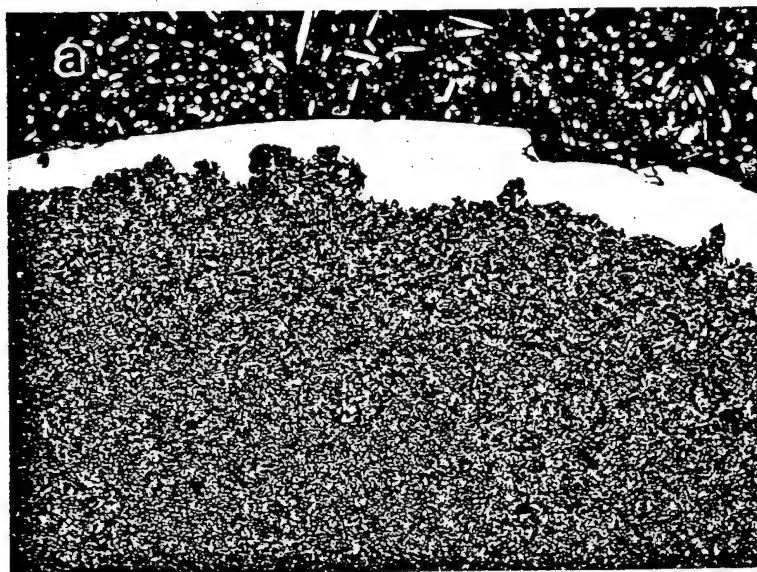
The extruded rods with plasma sprayed 6061 Al coatings showed very poor adhesion of the coating, and in fact, most of the aluminum coating was stripped from the Be-Al rods during extrusion. A small section from extrusion 591B, which had retained the Al coating through the extrusion process, was examined in the scanning electron microscope (SEM). This examination revealed a very rough Al coating/Be-Al interface, as well as a non-uniform coating thickness, which varied from 50 to 350 μm (Figure 3). This billet preparation technique, as carried out by the selected vendor, produced results significantly inferior to the other billet preparation techniques (Cu plating, Al cans, and Cu cans).

Tensile properties were obtained for four of the extrusions. These extrusions were the ones prepared from billets that were canned in either a copper or aluminum sleeve, or copper plated. Results of the tensile tests are shown in Table 3. Results for billets 589B, 590A, and 590B are consistent. The higher strength and low ductility of billet 589A is anomalous, and is likely a function of problems with the starting casting microstructure and chemistry, and not a function of billet canning technique.

Table 3. Tensile Properties of Extruded Be-Al

ID	Billet Prep.	0.2% YS(MPa)	UTS(MPa)	% E(12.7 mm gage)	% RA
589A	1.9 mm Cu can	440.3	486.2	5.6	1.6
589B	0.63 mm Cu plating	352.6	442.4	15.4	16.8
590A	1.9 mm Al can	370.6	466.0	16.6	15.4
590B	0.63 mm Al can	358.8	456.5	16.6	16.8

Based on the results of Task 1, copper plating was selected as the billet preparation technique for Task 2 billets. The one extruded billet that had been copper plated had the best surface quality of the six tested billets, and the smoothest interface between the Be-Al core and the cladding layer. It should be noted, however, that the smoothness of the interface is likely a function of the chemical surface preparation technique used on the billet prior to plating, and not just to the presence of a plated copper coating. Application of a similar chemical surface preparation technique prior to canning in copper or aluminum may result in similarly smooth interfaces, and needs to be tested. Although the plasma sprayed Al coatings were unsuccessful in this task, variations in the technique might, in the future, lead to improved results.



500 μm

Figure 3. Backscatter electron images showing Al plasma sprayed surfaces of extruded Be-Al. (a) 591B, transverse section, (b) 591B, longitudinal section.

5.0 Task 2: Production of Structural Shapes

5.1 Task 2: Billet Preparation

Task 2 was designed to demonstrate the capability of extruding a structural shape of moderate complexity of beryllium-aluminum composite. For this task, three beryllium-aluminum ingots were cast in molds measuring 63.5 mm diameter by approximately 200 mm length. The alloy composition (65-Be-33Al-2Ag) and the basic casting technique were the same as used in Task 1.

Each billet was machined to a diameter chosen such that the final diameter of the coated billet was approximately 50 mm. Cu plating was selected as the billet preparation technique for task 2 billets based on the results of Task 1. The copper plating was applied using the method developed in Task 1. The billet used for the first shaped extrusion was plated with a 1.27 mm thick copper coating; the billets for the second and third shaped extrusions were plated with 1.90 mm thick copper coatings.

5.2 Task 2: Extrusion Processing

The extrusion shape selected for this program was a modified "I" beam, and is representative of types of shapes previously used with other metal matrix composite materials. The design of the shaped extrusion die for task 2 is shown in Figure 4. The extruded product was evaluated for surface quality, mechanical properties and microstructure.

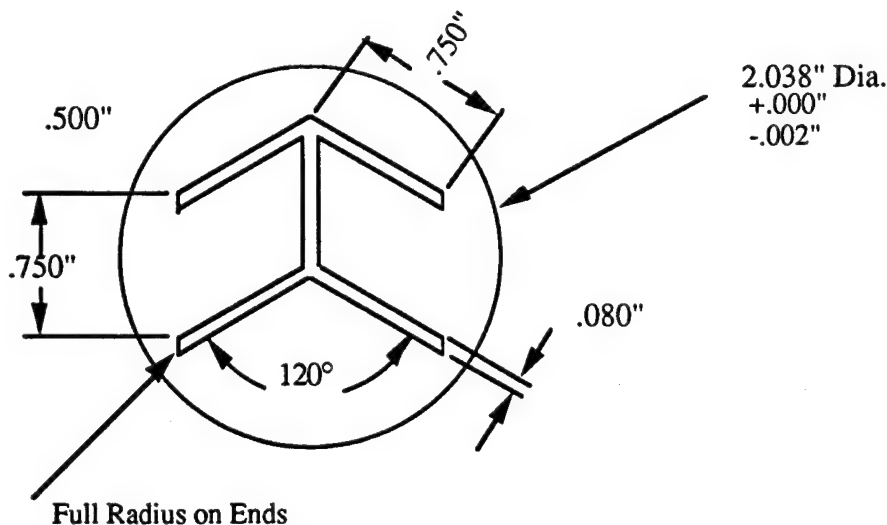


Figure 4. Task 2 shaped extrusion die design.

Extrusion of the three billets for Task 2 was done sequentially so that decisions about extrusion conditions could be made based on experience from each previous extrusion. Based on this experience, lubrication was found to be a critical parameter for the shaped extrusions, and was varied for each extrusion based on experience with the previous extrusion. Lubrication for the first shaped extrusion was the same as was used for Task 1, that is, graphite in oil lubrication (Lube-A-Tube) was applied to the extrusion press liner and extrusion die, and a graphite suspension lubricant (Spray Dag) was applied to the billet

prior to heating. Lubrication for the second shaped extrusion was changed to a lead/grease lubricant (Fiske 604D) for the liner and die, and a mixture of graphite powder, tungsten disulfide and water glass for the billet. The lubrication for the final shaped extrusion included Fiske 604D for the liner and die, and Spray Dag for the billet.

Each billet was heated to 450°C, then extruded with a ram speed of 6.4 mm per second on the 340 ton capacity extrusion press at NMI. The resulting extruded shaped rods were pickled in nitric acid to remove the copper cladding.

5.3 Task 2: Results and Discussion

Shaped rods with varying quality were produced from each of the three billets extruded for this task. The total extruded length in each case was on the order of 2 m. Examination of the first extruded shaped rod showed some tearing over approximately half the length of the rod at the fillet where the angles are small (60°) and sharp. No tearing was seen at the 120° angle in this extrusion.

To decrease or eliminate the amount of tearing seen in the first extrusion, modifications were made to decrease the amount of shear stress experienced at the 60° fillet in the subsequent extrusions. These modifications included increasing the thickness of the plated copper from 1.27 to 1.90 mm, hand blending the sharp corners in the extrusion die, and changing the lubrication system. The lubrication system used for the Task 1 extrusions and the first shaped extrusion of Task 2 is a common system for a number of applications, and was originally selected based on previous experience in which this lubrication system was successfully used for extrusion of clad Be-Al billets through a round die. The recipe for the mixture of graphite powder, tungsten disulfide and water glass that was substituted for the billet lubrication in the second shaped extrusion had been previously developed and optimized specifically for the extrusion of powder metallurgy based Be-Al composites.² The Fiske 604D lubricant used for the liner and die of the second shaped extrusion was selected since it is a lubricant that has been found to be beneficial in the extrusion of pure beryllium.

A significant improvement in the resulting shaped extrusion was seen for the second extrusion trial, which incorporated the process changes described above. No tearing was seen for the front 0.9 m of the extrusion. However, the rear 0.5 m of this shaped extrusion broke apart. Subsequent investigation revealed that the extrusion die appeared to have undergone a severe chemical attack during the extrusion process, and that the break up of the extruded rod was caused by the damage done to the die. The damage to the die was irreparable, and a new die had to be purchased for the final extrusion. The type of damage done to the die is unprecedented, and the exact cause of this damage has not yet been determined.

Due to concerns associated with the chemical attack on the die in the second shaped extrusion, the billet lubrication for the final shaped extrusion was changed back to the original graphite suspension used for the Task 1 extrusions and the first shaped extrusion. Problems were encountered with the operation of the extrusion press for the final shaped extrusion such that the first attempt to extrude this billet had to be aborted. The aborted attempt resulted in a cracked die and the mechanical upsetting of the starting billet. In order to extrude this final billet after the aborted attempt, the plated surface had to be surface

² C. H. Zenuk and P. Loewenstein, "Production Techniques for the Extrusion of Thin Lockalloy Shapes," Technical Report AFML-TR-68-239, submitted to Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, August 1968.

ground to the extent that the actual plating thickness on the billet was reduced from 1.90 mm to approximately 1.27 mm. In addition, this final shaped extrusion was produced using a cracked die, as described above.

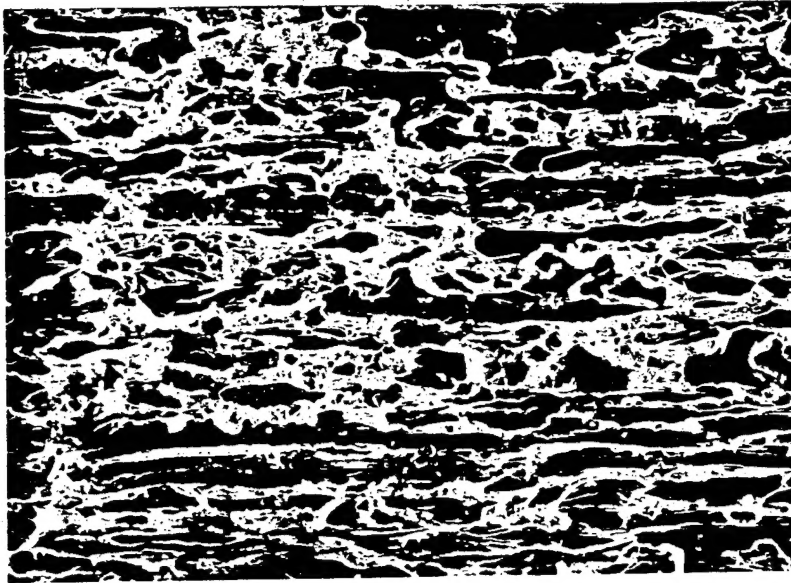
Results for the final shaped extrusion were similar to the results from the first shaped extrusion; that is, although the desired shape was produced, there was significant tearing at the 60° fillet. This result indicates that the lubrication change made for the second shaped extrusion may have led to the improvements seen for that extrusion. The results for the third shaped extrusion, however, were confounded by the difficulties encountered during the extrusion process, which were unrelated to the specific extrusion being performed.

Examination of the three extruded shapes revealed a significant degree of surface roughness on each extruded shape after the copper cladding was removed by pickling. Surface roughnesses on both the second and third extruded shapes were measured as approximately 325 rms. Figure 5 shows SEM images of the surfaces of the pickled extrusions. These images suggest that in part the surface roughness may be related to intrinsic characteristics of the composite Be-Al microstructure. This observation would suggest that modification of casting technique to provide a finer as-cast microstructure may lead to improved surface finishes in the extruded product.

Tensile properties were measured for several specimens taken from sections of the second shaped extrusion. These results are reported in Table 4. Tensile results for the shaped extrusion were below the tensile results for the round extrusions of Task 1. One explanation for the lower tensile results for the Task 2 shaped extrusions is that the larger diameter cast ingots required for the Task 2 extrusions contained porosity that may not have been fully healed during extrusion. Evidence for this explanation is shown in Figure 6. Figure 6 a and b shows the as-cast microstructure of a Task 2 ingot, which includes indications of porosity. Figure 6 c and d shows the fracture surface of the tensile specimen 6441-3B, whose properties are shown in Table 4. The fracture surface has a defect that appears to be related to the casting porosity. Further development in casting technique is required to produce fully dense larger diameter ingots that will lead to improved properties for the extruded product.

Table 4. Tensile Properties From Shape Extrusion 3

ID	0.2%YS (MPa)	UTS (MPa)	% E (25.4mm gage)	% RA
6441-3A	303.2	385.8	7.6	8.0
6441-3B	321.1	393.4	6.1	4.7



200 μm

Figure 5. SEM image of the surface of the first shaped extrusion after pickling.

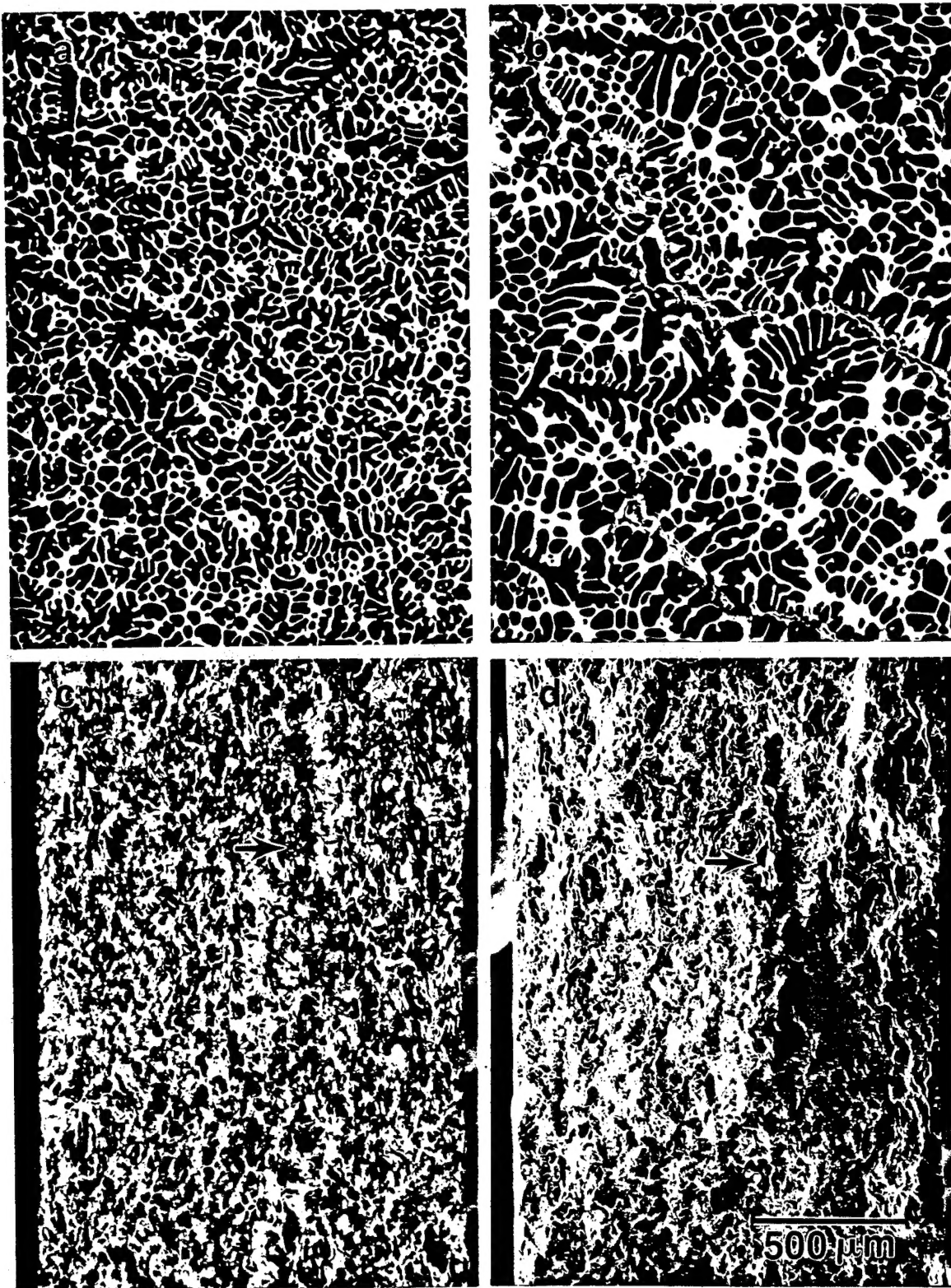


Figure 6. As-cast microstructures for Task 2 ingots showing (a) porosity free region (backscattered electron image) and (b) region with porosity (secondary electron image). Fracture surface of tensile specimen from shaped Task 2 extrusion showing defect related to ingot porosity (c) backscattered electron image and (d) secondary electron image.

6.0 Future Potential

Excellent mechanical properties were demonstrated for cast and extruded Be-Al composites in Task 1 of this program. Although mechanical properties for the shaped extrusions of Task 2 were below the properties of the simpler round extrusions of Task 1, the results of Task 2 indicate that further development of processing technique could lead to enhanced properties in shaped extrusions similar to those achieved in Task 1.

Required process improvements are in the areas of both ingot casting technique and extrusion processing. In the area of ingot casting technique, process improvements are required to produce porosity free larger diameter ingots that are required for many shaped extrusions. Microstructural refinement through controlled solidification in casting may also lead to improved mechanical properties, especially in thin sections, and to a decrease in surface roughness for the shaped extrusions.

In the area of extrusion processing, process modifications are required to produce long lengths of defect free shapes. The primary focus of process improvements should be in the areas of lubrication and die design. These improvements in extrusion processing would also lead to higher product yield, and thus cost reduction for the final product.

Additional potential for cost reduction would be through development of improved casting mold design, which would yield an ingot with a high quality surface that would not need to be machined prior to extrusion. Cost savings would then be achieved both through higher material yield and decrease in machining. Development of a process that incorporates a thin Al cladding through the extrusion process could also lead to cost reduction if the Al cladding did not need to be removed after extrusion. This should be the case if the final Al cladding made up no more than 3-5% of the total cross-section thickness such that there would not be a significant weight penalty for leaving it in place.

7.0 Conclusions

The major conclusions of the Phase I program can be summarized as follows:

- Production of Be-Al composites by casting and extrusion is a viable technology.
- Cast Be-Al ingots can be extruded with either an aluminum or copper clad surface.
- Excellent properties can be achieved in cast and extruded Be-Al rod. This demonstrates potential for properties in extruded Be-Al shapes.
- Be-Al composites can be cast and extruded into lengths of moderately complex shape, as demonstrated by the extrusion of the modified I-beam used in this Phase I program.